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Probe vehicle-based traffic state estimation method with spacing information and conservation law

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ABSTRACT

This paper proposes a method of estimating a traffic state based on probe vehicle data that contain spacing and position of probe vehicles. The probe vehicles were assumed to observe spacing by utilizing an advanced driver assistance system, that has been implemented in practice and is expected to spread in the near future. The proposed method relies on the conservation law of the traffic flow but is independent of a fundamental diagram. The conservation law is utilized for reasonable aggregation of the spacing data to acquire the traffic state, i.e., a flow, density and speed. Its independence from a fundamental diagram means that the proposed method does not require predetermined nor exogenous assumptions with regard to the traffic flow model parameters. The proposed method was validated through a simulation experiment under ideal conditions and a field experiment conducted under actual traffic conditions; and empirical characteristics of the proposed method were investigated.

1. Introduction

Probe vehicles are one of the most effective methods for collecting road traffic data because of their wide coverage area over time and space. In particular, probe vehicles equipped with global positioning system (GPS) that report their position and speed are commonly used at present (e.g., Herrera et al., 2010).

Traffic states are represented by the flow, density and speed. These variables can be estimated by using partially observed traffic data. This is known as traffic state estimation (TSE) and has been incorporated with GPS-equipped probe vehicles (e.g., Nanthawichit et al., 2003; Herrera and Bayen, 2010; Yuan et al., 2012; Mehran et al., 2012). In order to estimate the states, traffic flow models such as the Lighthill–Whitham–Richards (LWR) model (Lighthill and Whitham, 1955; Richards, 1956) and its successors have often been assumed and utilized. The LWR model is based on two assumptions: the fundamental diagram (FD; also known as flow–density relationship) and the conservation law (CL). The FD has a significant role in probe vehicle-based TSEs with regard to acquiring the flow or density from the observed speed. Most existing TSE methods assume some exogenous conditions on an FD (e.g., its functional form and parameters). However, an FD is a complicated phenomenon that involves various factors (e.g., road and user characteristics) and cannot be described or predicted completely. Therefore, such exogenous assumptions for an FD may negatively affect the estimation robustness. On the other hand, the CL should always be satisfied in the estimation model except at merging/diverging positions. Our interest is the TSE by using probe vehicle data without a predetermined FD. This requires, however, additional observed data.

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Recently, several technologies have been developed for acquiring information on the surrounding environment from a running vehicle. While their original and current purposes are for advanced driver assistance systems (ADASs), such as adaptive cruise control and autonomous driving (National Highway Traffic Safety Administration, 2013), they are also valuable for TSE because the spacing and speed of the vehicle must be measured precisely in order to enable effective ADAS. Seo et al. (2015) proposed a TSE method that simply aggregates such probe vehicle data to estimate flow and density. One of the deficiencies of Seo et al. (2015)'s method is its independence from traffic dynamics. For more sophisticated and precise estimation, traffic flow models need to be explicitly considered. The problem is that almost all existing traffic flow models utilize an exogenously given FD, even though the FD can be directly observed by ADAS-equipped probe vehicles.

The objective of this study was to develop and validate a method that estimates the traffic state based on the observed spacing and position data of probe vehicles by considering the traffic dynamics. The proposed method utilizes a CL to represent the traffic dynamics. On the other hand, it does not use an explicit FD in order to eliminate exogenous factors. The developed method was verified by using actual data taken from a field experiment performed on an urban expressway as well as synthetic data generated by simulation. Section 2 describes the development of the proposed method. Sections 3 and 4 describe its validation.

2. Estimation method

This section describes the proposed method of estimating traffic states based on observed spacing and position data from probe vehicles.

2.1. Concepts

The proposed method estimates traffic states in a road section where some of the vehicles in the traffic are probes that measure the geographic position and spacing of the vehicle ahead without any errors. The road section's schematics are assumed to be known to analysts. The probe vehicles' driving behavior is assumed to be the same as that of non-probe vehicles, i.e., the probes are randomly sampled from all of the vehicles. In addition, the traffic is assumed to be single-lane traffic that satisfies the first-in first-out (FIFO) condition in order to simplify the situation.

The spacing observed by a vehicle at a point depends on microscopic vehicular phenomena that depend on macroscopic traffic flow phenomena. For example, the spacing of a vehicle takes a volatile value that is often determined by whether the vehicle is the leader of a platoon or not; meanwhile, the formation of the platoon is mainly determined by the global traffic state. Therefore, aggregation is needed in order to estimate the global traffic state from the observed vehicular variables. In this method, the observed vehicular variables are aggregated based on the CL. Specifically, the number of vehicles between two specific probe vehicles is a constant along a section where merging/diverging positions (i.e., nodes in a road network) do not exist. This number of vehicles is estimated by aggregating the data observed by the two boundary probe vehicles. The estimation procedure is as follows:

Step 1 The number of vehicles between two consecutive probe vehicles and two consecutive merging/diverging positions is estimated based on the observed data of the two probe vehicles.
Step 2 The cumulative counts at the probe vehicle trajectories are calculated from the estimated number of vehicles.
Step 3 The continuous cumulative count over the entire time–space region is estimated by interpolating the cumulative counts at the probe vehicle trajectories.
Step 4 Traffic states (i.e., flow, density and speed) are derived by partially differentiating the continuous cumulative count.

Fig. 1 visualizes the relation among the cumulative count, vehicle trajectory, and traffic state (for details, see Makigami et al., 1971; Daganzo, 1997). The proposed method can be regarded as based on rectangles on the n–x coordinate plane, which is similar to the n–t Lagrangian coordinates of Leclercq et al. (2007) and van Wageningen-Kessels et al. (2013) and is identical to coordinates of T-model by Laval and Leclercq (2013), because the primary subject of estimation is the number of vehicles in the n–x rectangles. Steps 1 and 2 are described in Section 2.2; and steps 3 and 4 are described in Section 2.3.

2.2. Estimation method for cumulative count at probe vehicle's trajectory

Consider the time–space region $\mathbf{A}_m^j$ surrounded by

- trajectory of the m-th probe vehicle,
- trajectory of the leading vehicle of the $(m-1)$-th probe vehicle,
- the j-th merging/diverging position, and
- the $(j+1)$-th merging/diverging position.